Complex Permittivity Measurement of Reference Liquids using the Slotted Coaxial Line at Mobile Communication Frequencies

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Abstract

Complex permittivities of reference liquids were measured by a liquid holder of slotted coaxial line with a movable probe at mobile communication frequencies. The validity of the liquid measurement system was checked by experimental tests with the reference liquids proposed in IEEE Std. 1528-200X or IEC 106/61/CDV.
Key words : Slotted Coaxial Line, Complex Permittivity Measurement of Liquids.

Ⅰ. Introduction

The increasing popularity of mobile phones and radios has been accompanied with a growing concern for possible health effects from radio frequency(RF) emissions of these and other transmitting devices. Accordingly, the system that measure accurate quantity of electromagnetic fields inside the body of a user of these devices was developed[1]. At radio frequencies the mensuration, SAR(Specific Absorption Rate), is defined as the rate at which energy is absorbed per unit of mass per unit of time.

$$SAR = \frac{d}{dt}\left(\frac{dW}{dm}\right) = \frac{d}{dt}\left(\frac{dW}{\rho \cdot dV}\right) \quad or$$

$$SAR = \frac{|E|^2 \cdot \sigma}{\rho} \quad [W/kg]$$

where E is the total RMS E-field level(V/m) induced within the exposed tissue, σ is the conductivity(S/m), and ρ is the tissue density(kg/m^3).

Before a batch of simulated tissue can be used for SAR measurements, its electrical characteristics(dielectric constant and conductivity) must be determined to ensure that the simulated tissue was properly made and will simulate the desired human characteristics. In this paper, complex permittivities of reference liquids(methanol and DI water) were measured by a sample holder of terminated slotted coaxial line with a movable probe at 835 and 1,800 MHz. The performance of the coaxial slotted line system was verified by test results of these liquids.

Ⅱ. Electrical Characteristics Measurement in Liquids

2-1 Simulated Brain Tissue

The simulated brain tissue is a liquid that simulates the dielectric constant and conductivity of human tissue. Ingredients are consisted of water, sugar, salt, etc. and are shown in IEEE Std. 1528-200X[2].

2-2 Methods of Dielectric Property Measurement of Liquids

Table 1. The component for human brain tissue.

(mass %)

Frequency (MHz)		835	1800			
		Recip.1	Recp.2	Recp.3	Recp.4	Recp.5
Water		40.45	52.64	55.36	54.9	49.43
Sugar		57.0				
Salt		1.45	0.36	0.35	0.18	0.64
HEC		1.0				
Bactericide		0.1				0.5
DGBE			47	13.84	44.92	
Triton X				30.45		
Diacetin						49.43
Target-value	ε_r	41.5	40			
	σ	0.9	1.4			

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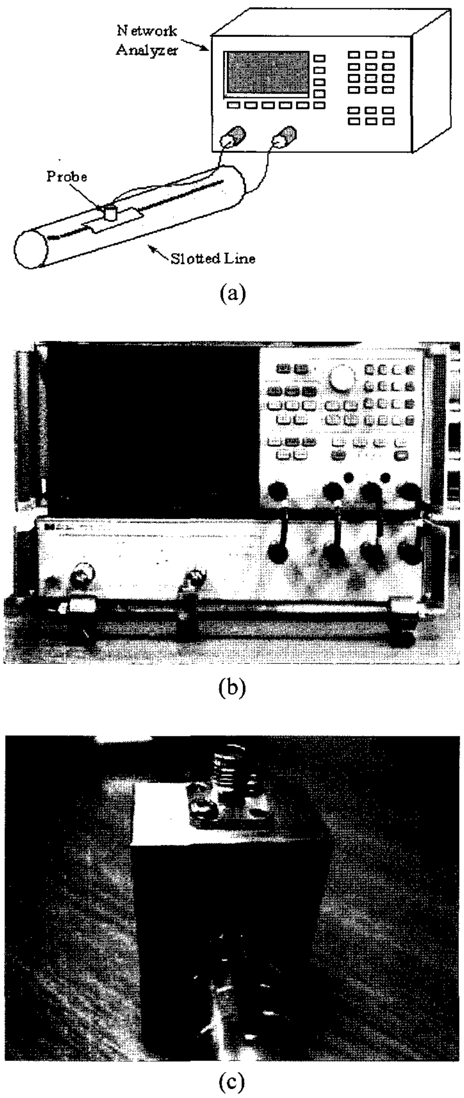
There are three different kinds of liquid testers and their corresponding methodologies are commercially available for the measurement of the dielectric properties of tissue-equivalent material. These are, ① terminated coaxial slotted line with a movable probe[3], ② the open-ended coaxial probe in contact with the sample and measuring its reflection coefficient(S_{11}), and ③ TEM-line filled with the test liquid.

In this paper, slotted coaxial line method was used for the measurement of two reference liquids, methanol and DI water. Fig. 1(a) shows the conceptual diagram of the coaxial slotted line with probe to measure RF amplitude and phase changes versus distance.

Fig. 1(b) is coaxial slotted line with the network analyzer, and Fig. 1(c) is magnified outlook near the slot. Dimensions of the coaxial slotted line in Fig. 1(c) are length=233 mm, the inside diameter of outer conductor, b=14 mm, diameter of inner conductor, a=6 mm.



(c)

Fig. 1. Coaxial slotted line system for the electrical characteristic measurement of liquids.

The characteristic impedance of this coaxial line is $Z_o = \sqrt{L/C} = (\eta_o / 2\pi)\ln(b/a) = 58.84\,\Omega$.

2-3 Complex Dielectric Property Measurement Theory

In a homogeneous medium with conductivity σ, permeability μ, and the complex permittivity $\varepsilon = \varepsilon' - j\varepsilon''$, sinusoidal wave equation and solution for propagating in the z direction is

$$\nabla^2 \overline{E} + \omega^2 \mu \left(\varepsilon' - j\varepsilon'' - j\frac{\sigma}{\omega} \right) \overline{E} = \nabla^2 \overline{E} - \gamma^2 \overline{E} = 0$$

$$E(\rho,\phi,z) = E^+(\rho,\phi)e^{-\gamma z} + E^-(\rho,\phi)e^{+\gamma z}$$

$E^+e^{-\gamma z}$ represents a TEM wave travelling in the $+z$ direction. $E^-e^{+\gamma z}$ is the reflected wave which is very much attenuated in typical lossy mixture in coaxial lines and thus usually ignored.

Propagation constant γ is by definition.

$$\gamma^2 = (\alpha + j\beta)^2 = -\omega^2 \mu \left(\varepsilon' - j\varepsilon'' - j\frac{\sigma}{\omega} \right)$$

$$\mathrm{Re}(\gamma^2) = \alpha^2 - \beta^2 = -\omega^2 \mu\varepsilon' = -\omega^2 \mu \varepsilon_r \varepsilon_o,$$

$$\mathrm{Im}(\gamma^2) = 2\alpha\beta = \omega\mu(\omega\varepsilon'' + \sigma) = \omega\mu\sigma_{effective}$$

Relative dielectric constant and equivalent conductivity in general lossy mediums are follows.

$$\varepsilon_r = \frac{\beta^2 - \alpha^2}{\omega^2 \mu \varepsilon_o}, \quad \sigma_{effective} = \frac{2\alpha\beta}{\omega\mu} \tag{1}$$

where: α = attenuation constant(Np/m)

β = phase constant(rad/m)

$\gamma_{effective}$= equivalent conductivity(S/m)

When V_1 is the voltage measured at one point near the input port connector end of the coaxial slotted line, and V_2 is the voltage measured at another point Δz (m) farther away from the connector.

$$|V_2| = |V_1| \exp(-\alpha \Delta z) \text{ and}$$

$$\alpha(Np/m) = -\ln |V_2/V_1| / \Delta z \tag{2}$$

Measured data by network analyzer do not give α and β in units of Np/m or rad/m respectively; so conversions to standard scales are necessary.

$$\alpha(Np/cm) = \ln(10) \cdot \alpha\ (dB/cm)/20,$$
$$\beta(rad/cm) = \beta(\deg/cm) \cdot \pi/180(rad/\deg) \qquad (3)$$

$\alpha(Np/m)$ and $\beta(rad/m)$ are obtained by multiplying equations (3) by 100 each and are substituted for equations (1). Amplitude and phase are measured along a 10 cm or 5 cm distance according to the test frequencies with 1 cm or 0.5 cm spacing between neighbouring test points, giving 11 total pick up points of slotted line. α and β are computed using the average of the slopes measured over a 5 cm or 2.5 cm distance separated. The slope and phase of 6 pairs are measured at 11 points and these are expressed in equation (4).

$$\alpha_{avg}(dB/cm) = \left|\sum_{n=1}^{6} \frac{dB_{n+5} - dB_n}{5\ or\ 2.5\ cm}\right| / 6$$
$$\beta_{avg}(\deg/cm) = \left|\sum_{n=1}^{6} \frac{\deg_{n+5} - \deg_n}{5\ or\ 2.5\ cm}\right| / 6 \qquad (4)$$

Where, ε_r and $\sigma_{effective}$ can be calculated by these two measured data.

III. Complex Permittivity Measurement in the Reference Liquids

Methanol(99 %) whose dielectric constant and conductivity are relatively similar to human brain tissue was used among 4 reference liquids(Methanol, DMS, deionised(DI) water, Ethanediol) proposed in IEEE Std. 1528-200X. DI water was also measured as reference. The temperature of measuring environment was 20.0±1 ℃. S_{21} was measured by the network analyzer, HP 8753C.

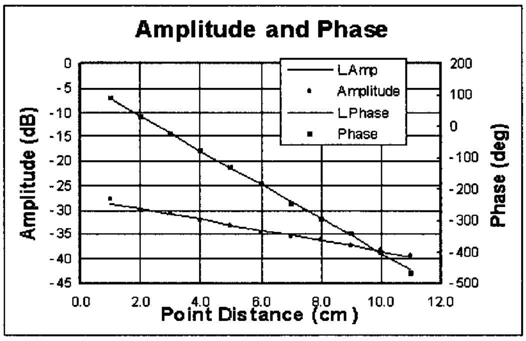


Fig. 2. Plots of amplitude and phase at 800 MHz.

Table 2. Magnitude and phases measured at 11 points along the slotted line at 835 MHz.

Point	Amplitude [dB]	Phase [°]
1	- 27.69	89.26
2	- 30.08	31.02
3	- 30.82	- 24.01
4	- 32.25	- 79.58
5	- 33.27	- 130.42
6	- 34.83	177.41
7	- 35.44	114.15
8	- 36.22	67.64
9	- 37.28	18.05
10	- 38.17	- 37.98
11	- 39.08	- 107.51

3-1 Methanol for 835 MHz

- The magnitude and phases at each measuring points that are equally separated 1 cm away each, are in Table 1. The data are plotted in Fig. 2.

- α_{avg} , β_{avg} calculated by equations (4).

α_{avg}			β_{avg}		
dB/cm	Np/cm	Np/m	deg/cm	rad/cm	rad/m
1.08	0.12	12.4	54.50	0.95	95.1

- Measured and target value of the liquid.

Results	Value	Target	% Off target
ε_r	29.04	31.37	- 7.44 (%)
$\sigma_{effective}$	0.36	0.35	2.51 (%)

3-2 Methanol for 1,800 MHz

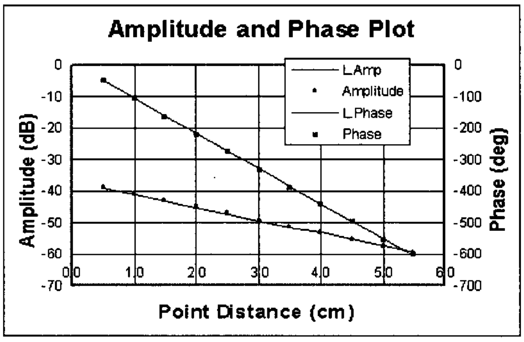


Fig. 3. Plots of amplitude and phase at 1,800 MHz.

· α_{avg} , β_{avg} calculated by equations (4).

α_{avg}			β_{avg}		
dB/cm	Np/cm	Np/m	deg/cm	rad/cm	rad/m
4.13	0.48	45.7	111.58	1.95	194.7

· Measured and target value of the liquid.

Results	Value	Target	% Off target
ε_r	25.1	25.5	− 1.75 (%)
$\sigma_{effective}$	1.30	1.27	2.55 (%)

3-3 DI Water for 835 MHz

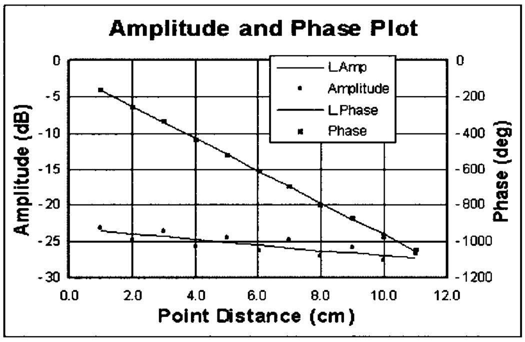


Fig. 4. Plots of amplitude and phase at 835 MHz.

α_{avg}			β_{avg}		
dB/cm	Np/cm	Np/m	deg/cm	rad/cm	rad/m
0.376	0.043	4.3	88.47	1.544	154.4

Results	Value	Target	% Off target
ε_r	77.8	80.0	− 2.80 (%)
$\sigma_{effective}$	0.20	0.17	19.34 (%)

3-4 DI Water for 1,800 MHz

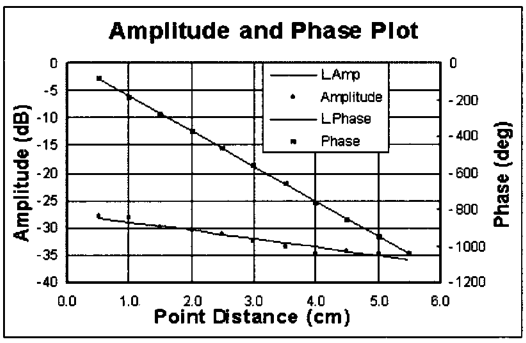


Fig. 5. Plots of amplitude and phase at 1,800 MHz.

α_{avg}			β_{avg}		
dB/cm	Np/cm	Np/m	deg/cm	rad/cm	rad/m
1.521	0.175	17.5	192.53	3.360	336

Results	Value	Target	% Off target
ε_r	79.1	79.4	− 0.35 (%)
$\sigma_{effective}$	0.83	0.78	6.17 (%)

Ⅳ. Conclusion

Complex permittivities of methanol(99 %) and DI water were measured by a sample holder of 50 Ω terminated slotted coaxial line with a movable probe at 835 and 1,800 MHz.

The measured value of methanol at 1,800 MHz was very close to the target value.

In case of DI water, standing wave of the amplitude along the slot was observed at both the test frequencies. Because the characteristic impedance of the coaxial line filled with liquids is very much different from 50 Ω, reflection occurred at the terminated coaxial line end was added to the incident wave because the reflected wave through the relatively low loss media was not sufficiently attenuated along the slotted line.

In order to measure the low loss liquid, the line should be longer than the line length in this paper.

The measurements showed that the conductivities are larger than the target values in all of the four tests. It means that the measured conductivities were higher than the ideal cases that the slot width is zero and the ohmic loss in the coaxial line is zero. There appeared a necessity that the slot width should be narrower and inner and outer of the coaxial line diameters should be increased for better accuracy of DI water. The phase constant β might be decreased a little bit from the case of the zero slot width because of the leaky wave out of the slot.

We can assume by the equation (1) that the measured values of ε_r with decreased β and increased α are always lower than the target values. The rate of a increase because of the losses seems bigger than rate of β decrease, which caused bigger conductivity measurement values than the targets.

Pretty good agreement between measurement data and target values for methanol at 1,800 MHz which has relatively higher loss was acquired.

In the more lossy material than methanol at 1,800 MHz, for example human brain tissue, this slotted line structure will give less off target values.

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